A COMPARISON OF CANOPY EVAPOTRANSPIRATION FOR MAIZE AND TWO PERENNIAL GRASSES IDENTIFIED AS POTENTIAL BIOENERGY CROPS

BY

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THESIS

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ABSTRACT

In the Midwestern U.S., perennial rhizomatous grasses (PRGs) are considered one of the most promising vegetation types to be used as a cellulosic feedstock for renewable energy production. The potential widespread use of biomass crops for renewable energy production has sparked numerous environmental concerns, including the impacts of land-use change on the hydrologic cycle. We predicted that total seasonal evapotranspiration (*ET*) would be higher for PRGs relative to maize resulting from higher leaf area and a prolonged growing season. We further predicted that, compared with maize, higher above-ground biomass associated with PRGs would offset the higher *ET* and increase water use efficiency (WUE) in the context of biomass harvests for liquid biofuel production. To test these predictions, *ET* was estimated during the 2007 growing season for replicated plots of *Miscanthus* X*. giganteus* (miscanthus), *Panicum virgatum* (switchgrass) and *Zea mays* (maize) using a residual energy balance approach. The combination of a 25% higher mean latent heat flux (λET) and a longer growing season resulted in miscanthus having ca 55% higher cumulative *ET* over the growing season compared with maize. Cumulative *ET* for switchgrass was also higher than maize despite similar seasonal-mean λET. Based on total harvested aboveground biomass, WUE was ca 50% higher for maize relative to miscanthus; however, when WUE calculated from only maize grain biomass was compared to WUE calculated from miscanthus harvested aboveground biomass, this difference disappeared. Although WUE between maize and miscanthus differed post-senescence, there were no differences in incremental WUE throughout the growing season. Despite initial predictions, above-ground biomass for switchgrass was less than maize; thus WUE was substantially lower for switchgrass than for either maize scenario. These results indicate that changes in *ET* due to large-scale implementation of PRGs in the Midwestern U.S. would likely influence local and regional hydrologic cycles differently than traditional row crops.

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INTRODUCTION

Growing population, rising fuel demand, and the link between fossil fuel emissions and global change have spurred interest in expanding bioenergy production to reduce fossil fuel demand and mitigate climate change (Sims et al., 2006; Tan et al., 2008). In the United States, corn ethanol has served as a first step towards reducing dependence on fossil fuels and meeting environmental goals. However, agricultural input demands (e.g. fertilizer, pesticides), relatively low production efficiency (Hamelinck et al., 2005), a perceived link between ethanol production and increased food prices (Msangi et al., 2006), and greenhouse gas emissions caused by indirect land-use change (Searchinger et al., 2008) have imposed limits on the benefits of producing ethanol from grain. Thus, development of a meaningful modern bioenergy industry will necessitate a transition from grain fermentation and the development of advanced technology for the conversion of cellulose to fuel.

Advanced cellulosic fuel production technologies are predicted to yield more fuel per unit land area with fewer inputs and fewer environmental impacts compared with grain-based ethanol production (Heaton et al., 2004; Hamelinck et al., 2005; Sims et al., 2006; Farrell et al., 2006). The perennial rhizomatous grasses (PRGs) switchgrass (*Panicum virgatum.* L.) and miscanthus *(Miscanthus* X. *giganteus*) are two candidate feedstocks currently being developed for use in bioenergy production (Heaton et al., 2008; Sanderson & Adler, 2008). These feedstocks have emerged as promising second generation ioenergy crops because they possess many of the traits necessary for sustainable biomass production (Heaton et al., 2004; Lewandowski et al., 2003; Sanderson & Adler, 2008). Despite advantages over traditional grain-based methods of producing liquid fuels, the development of a cellulosic fuels industry would generate a large demand for biomass that would in turn result in land use changes (McLaughlin & Walsh, 1999; Gurgel et al., 2007; Charlotte et al., 2008; Searchinger et al., 2008).

While large-scale planting of PRGs has the capacity for increased fuel production, it also suggests that there will be changes to these managed ecosystems, particularly with regard to the hydrologic cycle (Stephens et al., 2001; Hall, 2003; Fraiture et al., 2007; Charlotte et al., 2008). The root systems of perennials penetrate deep into the soil and generally have access to deeper soil moisture than annual crops (Neukirchen et al., 1999; Stephens et al., 2001; Hall, 2003). Leaf area index (LAI) is higher for PRGs relative to corn (Dohleman & Long, 2009), providing greater area for photosynthesis and transpiration.

These physiologically-based differences between PRGs and maize are further accentuated by a much longer growing season, differences in canopy architecture, and increased residue accumulation in the PRGs (Heaton et al., 2004; Dohleman & Long, 2009). Thus, it is critical to assess changes in evapotranspiration (*ET*), the combination of both ecosystem evaporation and transpiration, to assess the impacts of bioenergy crop growth on local and regional hydrology.

Our primary research objective was to estimate differences in water use among maize, miscanthus, and switchgrass. We predicted that the physiological, morphological, and phenological characteristics of PRGs will result in more water used during the growing season compared with maize. However, given the anticipated higher productivity of the PRGs, we also predicted that water use efficiency (WUE) will be greater for PRGs relative to maize. These predictions were tested using micrometeorological measurements over established stands of switchgrass, miscanthus, and maize over one growing season in 2007. This experiment provides the first ever side-by-side comparison of *ET* among these three species over a complete growing season.

MATERIALS AND METHODS

Site

Three replicate plots each of *Miscanthus x. giganteus* (miscanthus) and *Panicum virgatum* cv. Cave-in-Rock (switchgrass) were established in the South Farms at the University of Illinois in 2004 and 2005 as previously described (Heaton et al., 2008; Dohleman & Long, 2009). Maize cv. 34H35 (Pioneer Hi-Bred International) was planted at 0.76 m row spacing on 8-May, 2007 and emerged on 11-May, 2007. The same area had been planted with soybean in 2006 and 168 kg [N] ha^{-1} was applied prior to the planting of the maize crop, following typical agronomic practices in this region of the Midwestern U.S.A. No fertilizer was applied to either maize or switchgrass in 2006 or 2007. The plots measured ca 30 m x 60 m (0.2 ha) and consisted of mature homogenous plantings of each species planted on a Flanagan-Drummer silty clay loam (fine-silty, mixed, mesic Typic Endoaquolls). The plots were planted in a randomized complete block design (n=3) and were surrounded on all sides by production-scale plantings of maize.

Micrometeorology

Given the relatively small plot sizes, evapotranspiration was best estimated as the residual in the energy balance equation (Huband & Monteith, 1986; Jackson et al.,1987; Triggs et al., 2004):

$$\lambda ET = R_n - G_0 - H \qquad \text{Eq. 1}$$

where λ *is* the latent heat of vaporization (J kg^{-1}), ET is evapotranspiration (kg m^{-2} s^{-1}), R_n is net radiation (W m^{-2}; positive downward), G_0 is soil surface heat flux (W m^{-2}; positive downward), and H is sensible heat flux (W m^{-2}; positive upward).

The residual energy approach allows for estimation of λET by assuming that the net of energy fluxes due to photosynthesis, respiration, and heat storage within the canopy are negligible (< 1% of incoming radiation; Meyers & Hollinger, 2004). Within each plot, observations were obtained via micrometeorological instrumentation wired to a datalogger (models CR10X or CR3000, Campbell Scientific, Inc., Logan Utah, USA). The measurements of R_n, G_0 and H, as described below, were made in 10 s intervals and averaged over 10 min intervals throughout the growing season. Measurements for analysis began prior to canopy closure, day of year (DOY) 137 for PRGs and DOY 168 for maize and collected continuously until senescence. Data loss from instrument failure occurred but

represented less than 15% of total data points and, with only one exception, at least one plot was operational for all species at any given time period.

Net Radiation, R_n

Net radiation was measured using single-channel net radiometers (model Q*6 or Q*7; Radiation and Energy Balance Systems; Seattle, Washington, USA) in each plot. Corrections were made for wind speed using a mechanical cup anemometer (model 12102D; R.M.Young Company; Traverse City, Michigan, USA) according to the manufacturer's protocol. Net radiometers were positioned 4 m above the ground in the maize and miscanthus plots and 2.5 m above the ground in the switchgrass plots and remained at this height for the growing season. Prior to the growing season, all net radiometers were cross calibrated against a factory calibrated model Q*7 net radiometer that was not deployed into the field. Conditions where dew or precipitation interfered with data were excluded from the analysis. All net radiometers in the miscanthus plots were damaged during the last week of measurements. Values for R_n from switchgrass, which did not differ throughout the season from miscanthus, were substituted for this one week time period.

Soil heat flux, G_o

Soil heat flux, G_0, is calculated as:

$$G_0 = G_{10} + C\Delta z\left(\frac{\Delta T}{\Delta t}\right) \qquad \text{Eq. 2}$$

where G_{10} is the soil heat flux at 10 mm soil depth, C is the volumetric heat capacity (MJ m^{-3} °C^{-1}) ,and ΔT is the change in temperature in time increment Δt over soil depth Δz. One soil heat flux plate (model HFT-3; Radiation and Energy Balance Systems) was located in each plot, buried at a depth of 10 mm. Heat storage in the 10 mm of soil above each heat flux plate was obtained by placing a fine-wire thermocouple below the soil surface and above each heat flux plate. Since measurements of G_0 were limited to one replicate per plot and given the small size of the heat flux plates (ca 9 cm^2) the measurement of this flux was less robust than R_n and H. However, G_0 has been shown to have limited sensitivity on surface energy balance calculations (Kimball et al., 1994) particularly after canopy closure; therefore better characterization of G_0 through larger numbers of subsamples would have minimal impacts on calculated λET (Figure 2).

Sensible heat flux, H

Sensible heat flux (H) was determined using a modified gradient flux method as:

$$H = p_a c_p \frac{T_s - T_a}{r_a} \quad \text{Eq. 3}$$

where p_a is air density (kg m^{-3}), c_p the heat capacity of air (J kg^{-1} °C^{-1}), T_s and T_a the surface and air temperatures (°C), and r_a the aerodynamic resistance (s m^{-1}). Atmospheric resistance was modeled using different equations based on the wind speed, atmospheric stability, and canopy height (Jackson et al., 1987; Kimball et al., 1994, 1999; Triggs et al., 2004). Relative humidity was measured using a temperature and humidity probe (Model HMP-45C, Campbell Scientific, Inc.) enclosed in an aspirated radiation shield (Model 076B Motor Aspirated Shield, Met-One Instruments, Inc., Grants Pass, Oregon) in a single location in a Miscanthus plot at a height of 4.25m. Wind speed was measured using a mechanical anemometer (Model 12102D 3-cup anemometer with photochopper, R.M. Young Company, Traverse City, MI) and air temperature was measured using a thermistor (Model 107, Campbell Scientific, Inc) with a custom aspirated heat shield employing PVC pipe, an axial fan, and aluminum tape. These sensors were situated at a fixed height above ground to ensure that heights were no less than one meter above the plant canopy at maximum height. This corresponded to a measured height, which varied among the plots, of between 2.25 and 2.35 m for switchgrass, 4.25m and 4.75m for miscanthus, and 4.25m for corn. A temperature probe malfunction in one of the miscanthus plots occurred around day of year 180, thus the air temperature reading for this plot was set equal to the closest miscanthus plots for the remainder of the growing season. Surface temperatures were measured using infrared radiometers (model IRR-P, Apogee Instruments, Logan, UT, USA). These sensors were mounted 4 m above ground and positioned at 45 ° angles from horizontal facing south for all plots.

When wind speed (u) was less than 0.1 m s^{-1} during neutral conditions, defined as $|T_s - T_a| < 0.1$ °C, r_a was set to a value of 1720 s m^{-1} (Triggs et al., 2004). When u was less than 0.1 m s^{-1} under non-neutral conditions, defined as $|T_s - T_a| > 0.1$ °C, r_a was calculated as (ASHRAE 1972):

$$r_a = \frac{p_a c_p}{1.52 |T_s - T_a|^{1/3}} \quad \text{Eq. 4}$$

When u was higher than 0.1 m s^{-1} the following equation was used:

$$r_a = \frac{1}{u}\left\{\frac{1}{k}\ln\left[\frac{z-d+z_o}{z_o}\right]\right\}^2 \phi \qquad \text{Eq. 5}$$

Where k is Von Kármán's constant (0.4), z is wind measurement height (m), z_o and d are the roughness length (m; 0.1*canopy height) and zero plane displacement (0.65*canopy height), respectively (Campbell & Norman, 1998), and ϕ *is* a stability correction. Height data, measured in weekly intervals for each plot, was fitted to an equation that best described the measured heights throughout the growing season as in Bernacchi et al. (2007). While z_o and d are likely to differ among species and growth stages, the values used in this paper are based on those suggested for 'uniform plant canopies' (Campbell & Norman, 1998) and are assumed similar for all three species in this study as they are planted uniformly and are all considered tall grasses. A sensitivity analysis in which the values for z_o and d were changed to 0.08*canopy height and 0.8*canopy height, respectively, resulted in less than a 1.5% change in either H or ET (data not shown). For stable conditions when the crop surface was cooler than air temperature, defined as $T_s < T_a$, ϕ was calculated as (Mahrt & Ek 1984):

$$\phi = (1+15Ri)(1+5Ri)^{0.5} \qquad \text{Eq. 6}$$

and for unstable conditions, $T_s > T_a$, as:

$$\phi = \left\{\frac{1-15Ri}{1+K(-Ri)^{0.5}}\right\}^{-1} \qquad \text{Eq. 7}$$

Ri is the Richardson number and is solved as

$$Ri = \frac{g(T_a - T_s)(z-d)}{(T_a + 273.15)u^2} \qquad \text{Eq. 8}$$

and K is solved as

$$K = 75k^2 \frac{\left[\left(z-d+z_o\right)/z_o\right]^{0.5}}{\left\{\ln\left[\left(z-d+z_o\right)/z_o\right]\right\}^2} \qquad \text{Eq. 9}$$

Under certain conditions, unreasonably high values for H were calculated at night. Thus, conditions when R_n was less than 10 W m^{-2} and r_a was calculated as less than 10 s m^{-1}, the data was excluded from analysis.

Fetch Considerations

The 0.2 ha plots had a minimum functional fetch radius of only 15 m in the E-W direction and 30 m in the N-S direction which limited the possibility of using other

micrometeorological techniques for directly measuring ET, as discussed previously (Kimball et al., 1999; Triggs et al., 2004). Previous studies have shown a radius of 12.5 m to be sufficient to support accurate measurements using this residual energy balance approach (Ottman et al., 2001). The residual energy balance approach to estimating λET is reasoned to have lower fetch requirements as turbulent transfer processes are a logarithmic function of height above the surface (Kimball et al., 1994). The residual energy balance method is most sensitive to measurements of R_n and T_s (Kimball et al., 1994). Since gradients are strongest near the crop surface, the layer near the canopy is most important for determining H (Kimball et al., 1999). The measurement of T_s using infrared radiometers minimized the fetch requirements relative to using a gradient flux approach where air temperature is measured at multiple heights. Similarly, given the sensor size and location within the plots, neither R_n nor G_0 are likely to be affected by the relatively small fetch. This leaves u and T_a as the two measurements that necessitate fetch considerations. Previous attempts to correct T_a to compensate for the smaller fetch of 12.5 m for FACE experiments resulted in negligible changes in the magnitude of T_a (Triggs et al., 2004). The fetch issues associated with measuring wind speed at 4m above fragmented plant canopies are more difficult to correct for and likely add to the error associated with the measurements.

The previous analyses of fetch issues focused primarily on Free Air CO2 Enrichment (FACE) plots where the vegetation being measured is surrounded by the same species with the same canopy characteristics. In our study, the three species were surrounded on all sides by maize. Thus, the canopy height at maturity is similar, at least for maize and miscanthus, to the surrounding fields, thereby minimizing the gaps that might be introduced. However, a sensitivity analysis suggested the measurements most likely influenced by the fetch constraints are small (Kimball et al. 1994) relative to the differences we observed for the species measured in this study.

Biomass Sampling

As described in Dohleman and Long (2009), aboveground biomass was measured per unit land area on a biweekly basis. For miscanthus, 10 randomly selected tillers were taken from two randomly selected plants in each plot, and the total number of tillers on each plant was counted to scale the biomass of the sample to the individual plant. Samples were oven-dried at 75 °C until reaching a steady weight. Plant density was then used to scale sample weights to plot scale measurements. For switchgrass, the same protocol was

followed, but the tiller samples from all three plots were mistakenly merged into one sample, thus removing the possibility to determine plot error. For maize, two subsamples per plot were removed and dried as before to determine dry sample mass. No samples of any species were taken within 3m of the edge of a plot to avoid any border effects (Roberts et al., 1993). The last subsamples used in our analysis corresponded to the final day of micrometeorological measurements after the canopies were completely senesced.

Water Use efficiency

Water use efficiency (WUE) was calculated from the total *ET* over the growing season and the biomass harvest that corresponded to the final day of micrometeorological measurements which differed among the crops. The biomass components that were used for the WUE calculations are based on the biomass that was removed at harvest for the purpose of energy production. Biomass that would not be taken, including all below-ground components, fallen residue, and portions of the tillers that were left standing after harvest, were not included. For corn, WUE is divided into two metrics; one similar to the PRGs where all aboveground biomass is considered and a second in which only the grain biomass is considered. The latter scenario is used as the 'current' U.S. ethanol production scenario where all ethanol production is based on grain fermentation.

Meteorology

For the purpose of describing the site meteorology, air temperature, relative humidity, and precipitation were collected from a weather station located in the center of the research field. The Palmer Crop Moisture Index (PCMI), calculated from temperature, precipitation, and modeled soil water content, was used to estimate short-term moisture conditions (Palmer 1968). PCMI values between -1 and 1 are indicative of normal moisture conditions, with values less than -1 suggesting more droughted conditions, and greater than 1 suggesting overly moist conditions. The 30-year mean PCMI value for the region containing this site is ca 0.4 (e.g., Bernacchi et al., 2007).

Data Analysis

Micrometeorological data were collected in 10 s intervals and averaged over 10 min. intervals throughout the growing season. Data points associated with instrument error or unfavorable meteorological conditions were removed from the dataset. These conditions were defined as periods when sensor accuracy was visibly diminished and were mostly associated with periods of heavy precipitation and occasionally with heavy dew formation. The removal of these data points has little effect on the estimation of *ET*, as evaporation

rarely occurs during precipitation, never occurs during dew, and because these conditions influenced all three species in unison. Means of the λET were calculated for each species for the entire growing season to represent the total growing season water demand. All three species experienced a closed canopy from day of year 190-235, and this time period was analyzed separately to reflect the influences of physiological differences among the species. Mean values of latent heat flux (λET) for the respective time periods were summed and converted to ET (mm) using the latent heat of vaporization and the density of water. The difference in ET among species was statistically tested using a randomized complete block analysis of variance (PROC MIXED, GLM3 SAS 9.1, SAS Institute, Cary, NC). Assumptions of normal distribution were verified using Levene's test of equality of variance and a proc univariate analysis for normality of data. Given the variability and low replicate number inherent within large field experiments, $\alpha = 0.10$ was used in all cases to reduce the probability of Type II error. A Tukey's corrected *a priori* means separation was used to determine significant differences between species.

A comparison of regressions technique was used to test differences in accumulated biomass vs. accumulated ET (Mead & Curnow, 1983). This technique requires a polynomial that accurately reflects the relationship between accumulated biomass vs. water use. A 2nd order polynomial was shown to fit this criteria and was fitted first to all three species together and then to each species separately. The goodness-of-fit for each separate curve was compared with the goodness-of-fit for one line representing all data. The type 3 sum of squares (i.e., error variances around each model) and associated degrees of freedom for lumped vs. separate fits were used to compute F-ratios associated with tests of homogeneity of the fitted polynomials (Mead & Curnow, 1983; Potvin et al., 1990). Significant values for this test were set *a priori* at $p < 0.05$.

RESULTS

Meteorology/climatology

The 2007 growing season was slightly drier and warmer than the 30 year average as calculated by the Midwest Regional Climate Center (http://mrcc.sws.uiuc.edu/). Temperatures were ca 1° C warmer than the 30 year average for the year, and ca 1.4° C warmer during the growing season (DOY 140-300). Annual and growing season precipitation were ca 21 % and ca 22% less than the 30 year average, respectively. However, the Palmer Crop Moisture Index (PCMI) for Illinois Climate Division 5, which includes the fields in this study, only dropped below -1 once, for a period lasting ca 7 days (Figure 1). Solar radiation, wind, and other meteorological factors were within normal ranges of annual variation (Figure 1).

Energy Fluxes

Two days from the growing season were selected to represent the diurnal trends for each of the measured energy fluxes (Figure 2). Day of year 196 had very little cloud cover during the daylight hours, with no significant differences in R_n observed among the three species (Figure 2). Soil heat flux increased throughout the day until solar noon at which point it began to decline. This diurnal pattern was similar for all three species. Sensible heat flux was relatively steady throughout the day for miscanthus and maize, whereas switchgrass showed a more pronounced increase in H until midday. All three species had high rates of λET during the daylight hours, but the higher H for switchgrass resulted in a lower peak value of λET (Figure 2). The overcast day, DOY 209, showed much more variability in R_n, H, and λET throughout the day and the differences among the species are much less (Figure 2).

Seasonal patterns in R_n were closely matched among the three species (Figure 3). Day to day variability in daily mean R_n was observed as a consequence of meteorological conditions; however, no clear species effect in R_n was observed, either over the growing season as a whole or over the period in which the three canopies were closed (Figure 3). Similarly, there are few differences in G_0 among the three species (Figure 3). There were observable differences in H among the three species, with switchgrass showing the highest H and miscanthus the lowest (Figure 3). This was consistent across most of the growing season, except for after day of year 240 when H began to increase for maize. From this

point on, maize had the highest H of the three species. The mean daily λET followed the inverse pattern of H (Figure 3). When averaged over the growing season, Miscanthus had the highest mean λET and there were no differences observed between maize and switchgrass (Table 1). The same pattern is apparent when considering the period of time in which all three canopies were closed (Table 1; Figure 3). Despite the lack of statistically significant differences between maize and switchgrass, there are lower rates of λET for switchgrass when the three species all experience mature, pre-senescent canopies (Figure 3; Table 1).

ET and Water Use Efficiency

As determined from emergence to senescence for the PRGs and from planting to senescence for the maize, the total growing season was longer for the PRGs by 33 days. Over their respective growing seasons, miscanthus had ca 55% higher and switchgrass 25% higher ET compared with maize (Table 1). While the three species showed relatively similar water use during the period when the canopies were mature, the large disparity in water use between maize and the perennial species is attributed to the length of growing season (Figure 4). Further, despite the difference in the growing season being only 33 days, it is clear that ET has started to decrease around 20 days before complete senescence for maize (Figure 4).

Water use efficiency based on above-ground harvested biomass was lowest for switchgrass and highest for maize (Table 1). However, when only harvested grain biomass was used to calculate WUE, the value for maize decline by almost one-third (Table 1). The amount of water used per unit of biomass accumulated differed among the three species based on a regression analysis ($F_{2,26} = 14.06$, $p < 0.01$), but these differences were driven by a strong deviation of switchgrass from the other two species (Figure 5). The relationship between incremental biomass accumulation vs. ET was similar between maize and miscanthus ($F_{1,16} = 3.97$, $p > 0.05$).

DISCUSSION

This study tested the prediction that perennial rhizomatous grasses (PRGs), which are likely to increase in percent coverage over the Midwestern U.S. as the demand for cellulosic biomass increases, evapotranspire more than maize. It also tested whether the higher biomass production associated with miscanthus and switchgrass was sufficient to offset the higher water use to result in an improved water use efficiency compared with maize. Contrary to our predictions, switchgrass did not yield higher biomass than maize. Total season water use was 954 mm for miscanthus, 764 mm for switchgrass, and 611 mm for maize, supporting the hypothesis that the PRGs will use more water over the duration of the growing season. Despite the higher productivity of miscanthus, WUE, at ca 19 kg ha^{-1} mm^{-1} was similar to maize at ca 18.6 kg ha^{-1} mm^{-1} (Table 1). Switchgrass used more water than maize but had lower harvested biomass; thus WUE for switchgrass was about half of the values measured for the other two species.

The 2007 growing season was drier than the 30 year average; however, at only one point in the growing season did the Palmer Crop Moisture Index drop below -1 (a low of -1.1 was achieved around mid-June) signifying 'abnormally dry' conditions (Figure 1). Throughout the rest of the growing season PCMI values fell within the 'Slightly Dry/Favorably Moist' category. Thus, although this season was slightly drier than normal, there is no indication of drought conditions or plant stress e.g., low yields or low harvest percentages (Dohleman & Long 2009).

The perennial nature of miscanthus and switchgrass results in a longer growing season and more opportunity to evapotranspire relative to maize. Mean λET was 25% higher for miscanthus relative to maize and dropped to only about 18% higher than maize when considering the time period when both canopies were closed (Table 1). Thus, for miscanthus, there is not only the effect of a longer growing season, but also physiological or morphological factors that drive increased ET. In contrast, switchgrass mean seasonal and mean 'mature canopy' λET was not statistically different from maize (Table 1). Given the small difference in mean λET, the higher ET for switchgrass relative to maize is likely dominated by the longer growing season (Figure 4). These results suggest that a combination of physiological and morphological factors, in addition to growing season length, drive the observed differences among the species. Potential morphological differences include mean root mass and distribution (Neukirchen et al., 1999), LAI and

aboveground biomass (Heaton et al., 2008; Dohleman & Long 2009). Differences among the species in stomatal conductance, which is shown to be closely coupled to canopy water use (e.g., Bernacchi et al., 2007), could also drive the differences in λET.

During the times when the PRGs are evapotranspiring and the maize field is fallow some evaporation in maize will occur. While this component of *ET* was not considered here, rates of evaporation outside of the growing season are shown to be quite small relative to what occurs during the growing season. For example, a recent study shows that ca 80% of the annual *ET* in a maize/soybean ecosystem occurs during the three to four month growing season (Suyker & Verma, 2009). The remaining 20% is evapotranspired during the remaining months, which, when considering the difference in growing season lengths between the PRGs and maize, amounts to a very small percentage. Measurements of λET over the fallow maize field were not measured in this study. However, when the growing season for maize was extrapolated to the same length as the perennial grasses, the total amount of ET for maize increased to 763 mm, similar to the amount of water evapotranspired from switchgrass. It is unlikely, however, that the evaporation from a fallow maize field could account for the large differences observed between maize and miscanthus.

When assessed over the entire growing season and using total above-ground biomass, WUE was lowest for switchgrass and highest for maize. The difference in WUE between maize and miscanthus is minimized when, instead of using the total above-ground biomass, only the grain component of maize is used in calculating WUE (Table 1). Since residue removal is known to have negative implications for sustainability of maize (Blanco-Canqui & Lal, 2009; Mann et al., 2002; Andrews, 2006), there exists a trade-off between maximizing biomass harvest to increase WUE and agricultural sustainability. Since the purpose of these ecosystems are for the sustainable production of feedstock for renewable energy production, the corn-grain WUE scenarios is a more relevant comparison with the perennial species. The relationship between biomass accumulation and *ET* was similar between miscanthus and maize (Figure 5), but why does the end of season WUE between these species differ (Table 1)? This disparity can be partially explained through losses in above-ground biomass for both species after senescence, but to a greater extent for miscanthus (Dohleman & Long, 2009). The loss in standing biomass immediately following senescence for miscanthus appears to be exceptional in this measurement season (Clifton-

Brown et al., 2001; Heaton et al., 2008; Dohleman & Long, 2009). Similarly, the loss in above ground biomass for maize suggested a harvest index of 0.66, which is much higher than typically measured (e.g., Tollenaar et al., 2006). Therefore, these results may underestimate the total seasonal WUE for both miscanthus and maize.

The values for WUE calculated from total season *ET* and corn grain biomass correspond well with the range of values reported by a number of previous studies conducted within several management practices and climate regimes (Hatfield et al., 2001; Suyker & Verma, 2009; Zwart et al., 2004). Mean WUE averaged over the globe was estimated at 18 ± 6.9 kg ha^{-1} mm^{-1} (Zwart et al., 2004) which are remarkably similar to the values obtained in this study (18.6 kg ha^{-1} mm^{-1}). Similarly, a study conducted in Nebraska, USA calculated WUE as 20 kg ha^{-1} mm^{-1} (Suyker & Verma 2009).

The differences among these three species' water use revealed valuable insights to the potential environmental impacts of second-generation bioenergy crop growth. Given the demonstrated increases in *ET* associated with the growth of second-generation bioenergy crops both temporally and quantitatively, we can expect changes in the environmental services tied to the hydrological cycle (Stohlgren et al., 1998; Brown et al., 2005; Li et al., 2007). Our study demonstrated increased seasonal *ET* associated with the growth of second-generation bioenergy crops driven by a combination of physiological, morphological and phenological differences among these three species. Therefore, potential large scale plantings of bioenergy crops could increase *ET,* thereby decreasing surface temperatures (Georgescu et al., 2009), increasing humidity, increasing precipitation and cloud cover, and decreasing solar radiation (Sellers, 1997; Bounoua et al., 2002; Findell, 2007). Increased *ET* associated with PRGs could also impact runoff and groundwater quality/quantity, soil moisture, and river flow (Stohlgren et al., 1998; Brown et al., 2005; Li et al., 2007). The primary impacts of altered *ET* (e.g. soil moisture) would also affect secondary changes, such as rates of carbon sequestration or soil respiration (Pastor & Post, 1986; Ma, 2000), and soil nitrogen budgets (Pastor & Post, 1986). Depending on the fraction coverage of PRGs grown in a region, the important link between vegetation and hydrology should be a major consideration in sustainable biomass production.

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APPENDIX

Table 1. Latent heat flux (*λET)*, cumulative water use and water use efficiency (WUE) for *Miscanthus* X. *giganteus* (miscanthus), *Panicum virgatum* (switchgrass) and *Zea mays* (maize) estimated using a residual energy balance approach. Biomass data used in the calculations of WUE for miscanthus and maize is from Dohleman & Long (2009) and for switchgrass is from Dohleman et al. (unpublished data). Values with differing superscript letters signify statistical differences at $p < 0.05$.

Seasonal Values	Elapsed Days	Mean λET (W m^{-2})	Water use (mm)	WUE (kg ha^{-1} mm^{-1})
miscanthus	166	159.7 ± 2.8^{a}	954.6 ± 16.4^{a}	19.1 ± 0.3^{a}
switchgrass	166	127.9 ± 5.6^{b}	764.3 ± 33.7^{b}	9.7 ± 0.4^{b}
maize	133	127.8 ± 4.8^{b}	611.9 ± 23.2^{c}	29.7 ± 1.1^{c}
maize grain	133	127.8 ± 4.8^{b}	611.9 ± 23.2^{c}	18.6 ± 0.8^{a}
Mature Canopy (DOY 190-235)				
miscanthus	45	171.4 ± 0.2^{a}	277.7 ± 0.4^{a}	-
switchgrass	45	144.8 ± 6.6^{b}	234.6 ± 10.7^{b}	-
maize	45	150.6 ± 3.7^{b}	243.9 ± 5.9^{b}	-

Figure 1. Daily maximum vapor pressure deficit (VPD) and Palmer Crop Moisture Index (Palmer, 1968) (top panel), daily maximum and minimum air temperature (middle panel) and daily total solar radiation and precipitation (bottom panel) throughout the 2007 growing season.

Figure 2. Net radiation (R_n), soil heat flux (G_0), sensible heat flux (H) and latent heat flux (λET) for a mostly sunny (left column, day 215) and an overcast (right column, day 209) day during the 2007 growing season. Open symbols represent switchgrass, grey symbols maize and black symbols miscanthus. Error bars represent one standard error around the mean of three replicates.

Figure 3. Daily mean values of net radiation (R_n), soil heat flux (G_0), sensible heat flux (H) and latent heat flux (λET) over the 2007 growing season for switchgrass, maize and miscanthus. The left panels show the entire growing season and the right panels show an expanded view of the time increment during which the canopies for all three species were closed. Symbols and error bars are as in Figure 2.

Figure 4. Contour maps showing latent heat flux (W/m^2) over the diurnal time course (Y-axis) throughout the 2007 growing season (X-axis) for miscanthus (top), switchgrass (middle) and maize (bottom).

Figure 5. Aboveground biomass as a function of water use during the 2007 growing season for miscanthus, switchgrass and maize. For each point, the total water used was determined according to the time in which a biomass harvest was performed. Data are only presented for pre-senesced biomass harvests. Biomass data are from Dohleman & Long (2009) for miscanthus and maize and from Dohleman (unpublished data) for switchgrass. The line represents a 2^{nd} order polynomial fitted to the miscanthus and maize data and symbols and error bars are as in Figure 2.

Figure 1

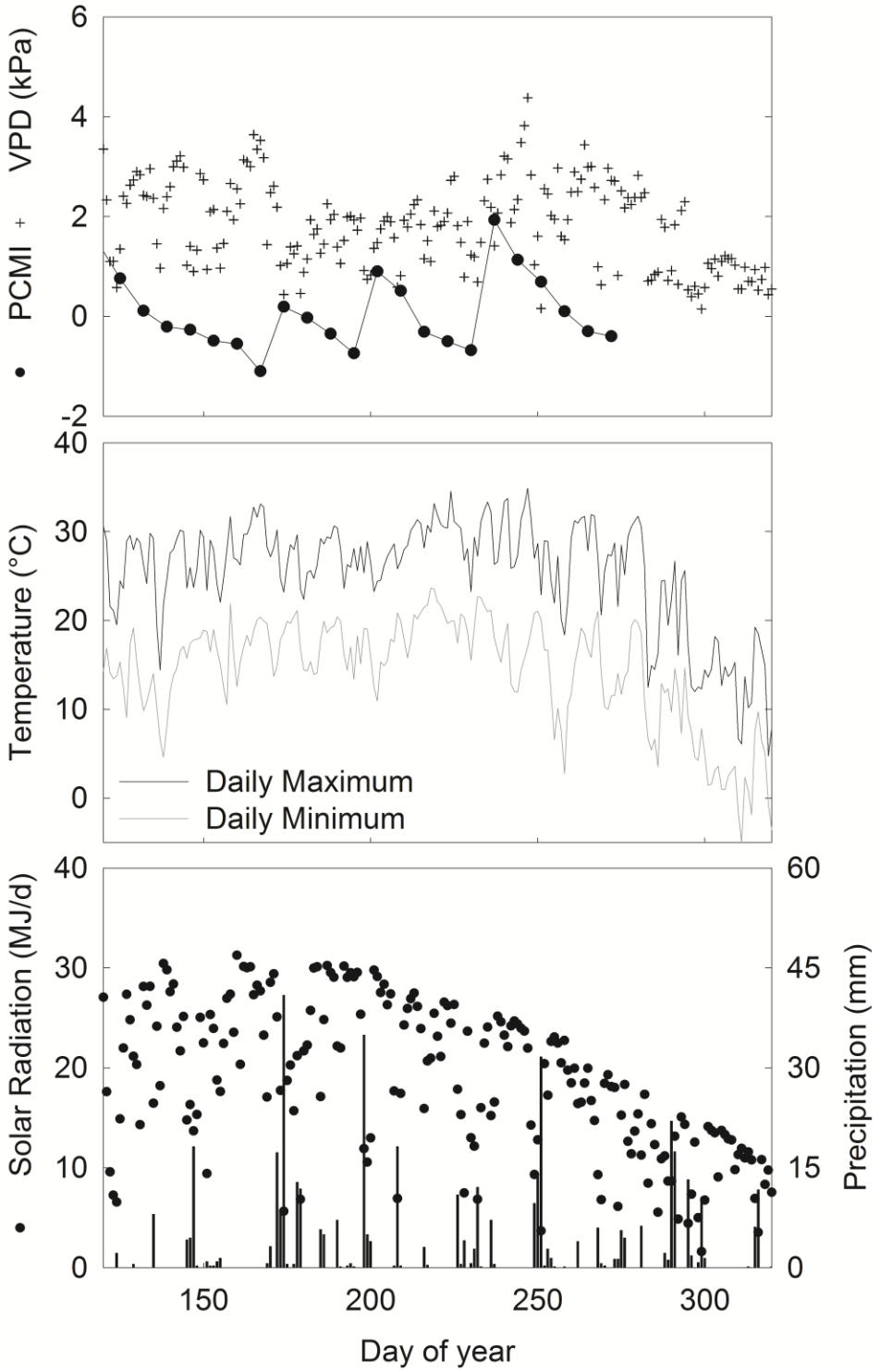
PCMI
VPD (kPa)
Temperature (°C)
Daily Maximum
Daily Minimum
Solar Radiation (MJ/d)
Precipitation (mm)
Day of year

Figure 2

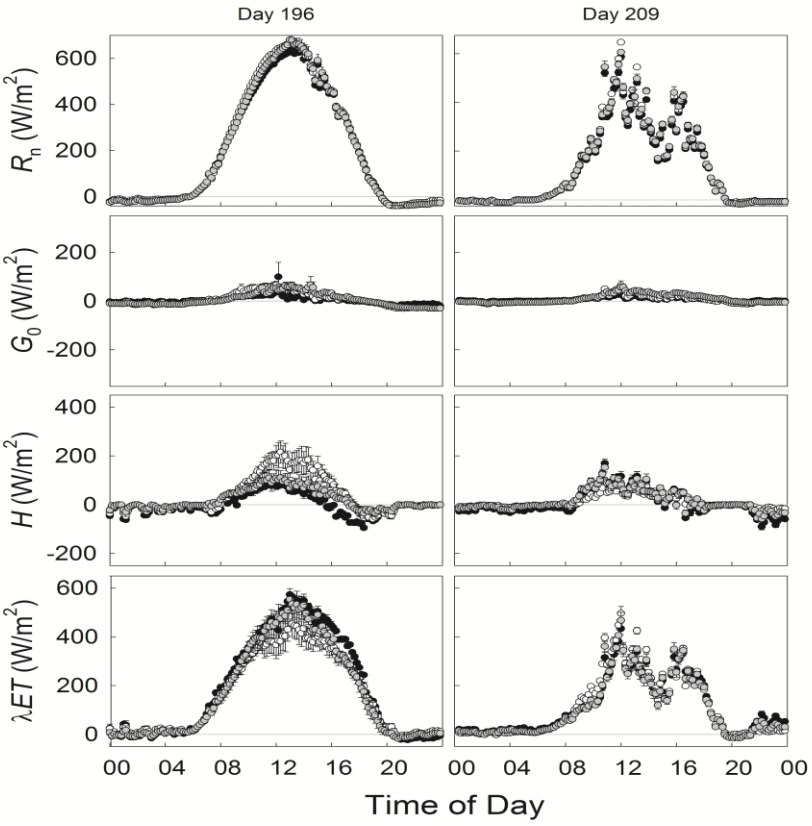
Day 196
Day 209
R_n (W/m^2)
G_0 (W/m^2)
H (W/m^2)
λET (W/m^2)
600
400
200
0
-200
00
04
08
12
16
20
Time of Day

Figure 3

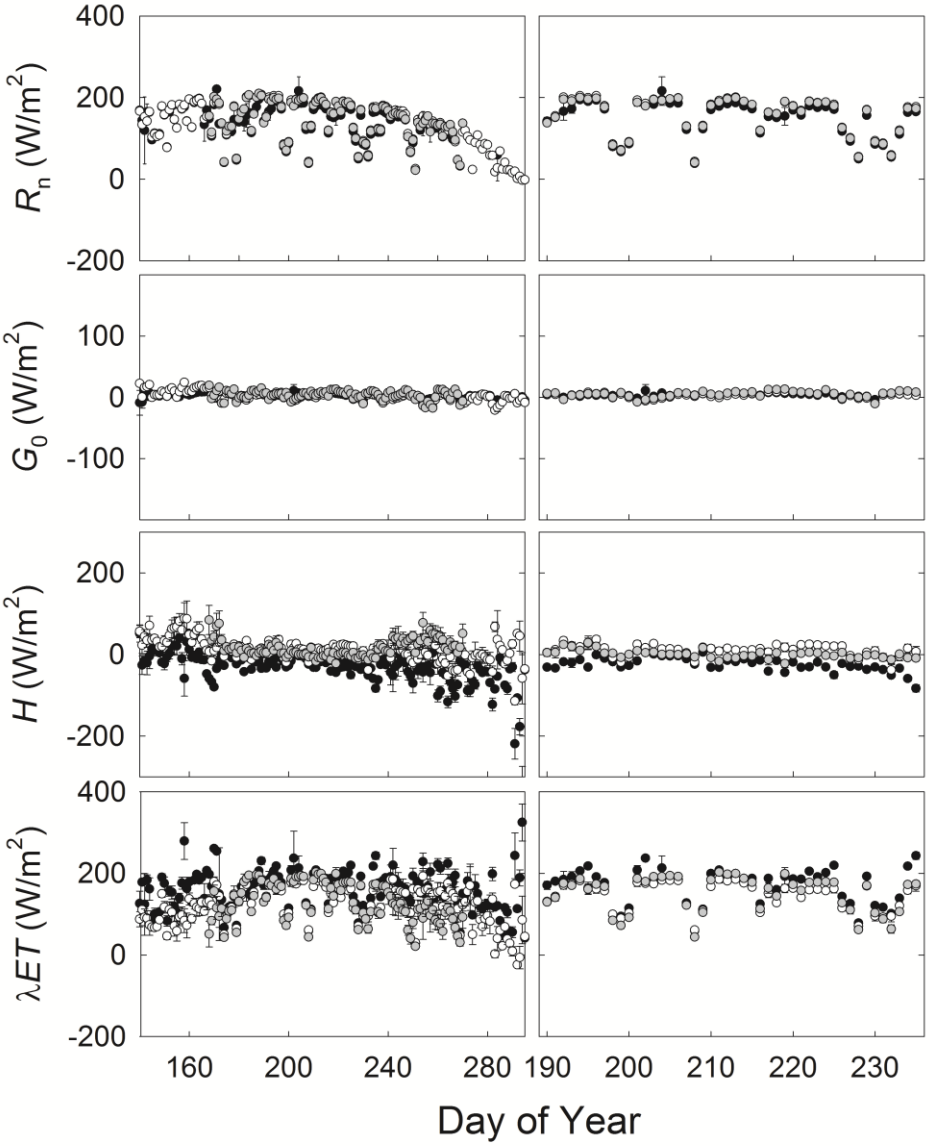
400
200
0
-200
R_n (W/m^2)
100
0
-100
G_0 (W/m^2)
200
0
-200
H (W/m^2)
400
200
0
-200
λET (W/m^2)
160
200
240
280
190
200
210
220
230
Day of Year

Figure 4

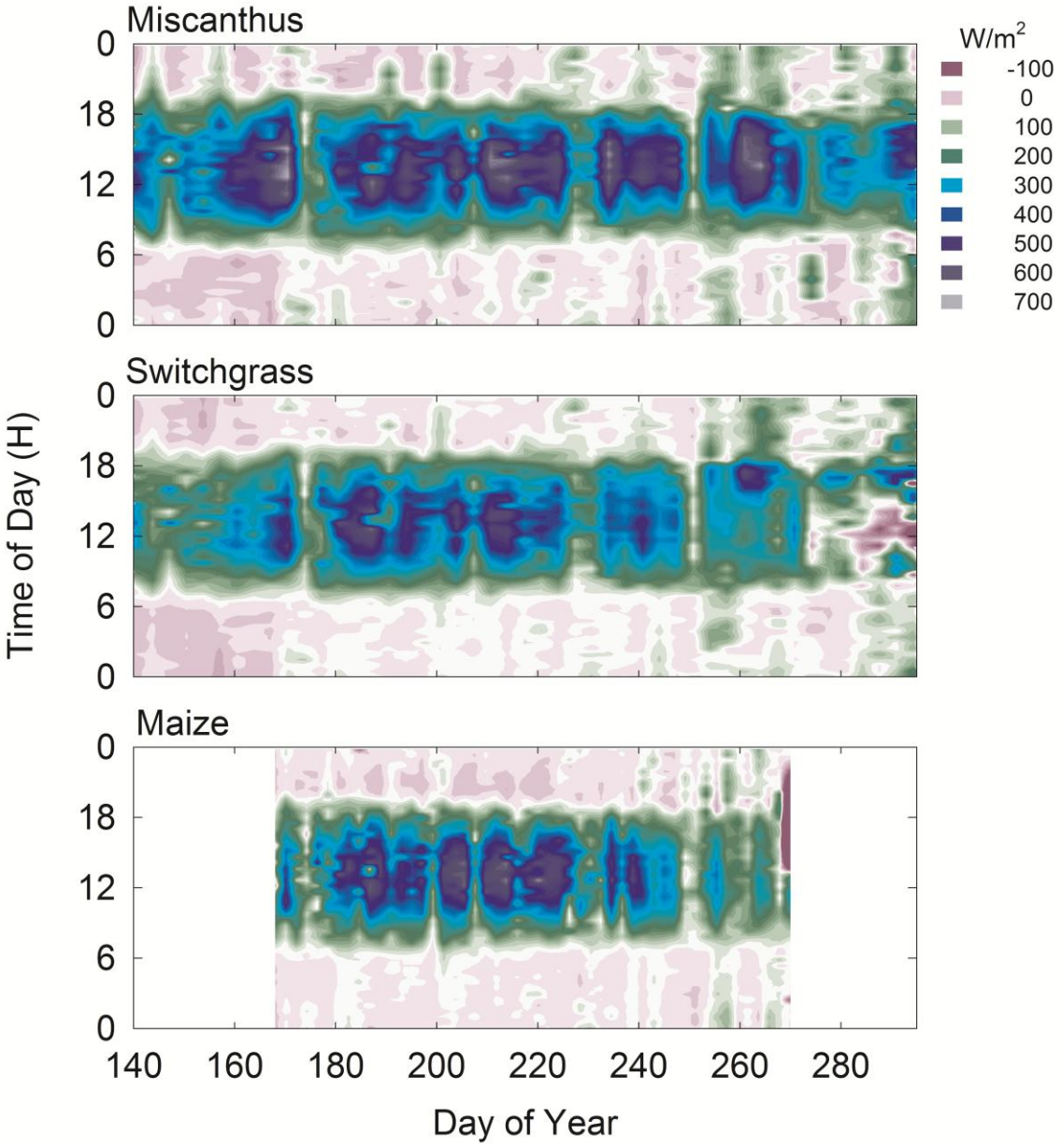
Miscanthus
Switchgrass
Maize
W/m2
-100
0
100
200
300
400
500
600
700
Time of Day (H)
0
18
12
6
0
140
160
180
200
220
240
260
280
Day of Year

Figure 5